# HOW CDTE SOLAR CELLS OPERATE: DETERMINING COLLECTION USING BIFACIAL DEVICE CHARACTERIZATION

D. Desai, S. Hegedus, B. McCandless, R. Birkmire, K. Dobson, D. Ryan
Institute of Energy Conversion, University of Delaware, Newark, DE 19716 USA

## ABSTRACT

The fundamental mechanisms governing carrier transport and in CdTe solar cells are not well established. Effects of diffusion length (L), depletion width (W), primary heterojunction vs. back junction are not well correlated with the CdTe thickness (t), or back contact. Bifacial analysis provides quantitative insight into CdTe device operation by separating the effects of front and back junction. Back spectral response ($SR_B$) was analyzed to evaluate L and W. Front spectral response ($SR_F$) is nearly unaffected by L or W. $SR_B$ and back $J_{sc}$ are higher for thinner cells as $SR_B$ is limited by diffusion across the field free region that is smaller for thinner cells. Bifacial characterization results indicate a photosensitive back barrier. There is no evidence of a back junction and we conclude that a single junction determines recombination current. These results establish that performance for AM1.5 light through front contact is determined primarily by voltage dependent collection, not diffusion length.

## INTRODUCTION

The operation of CdS/CdTe solar cells in relation to the device structure and processing parameters still remains somewhat obscure. Fundamental carrier transport analysis is complicated due to effects such as voltage dependent collection, photoconductive CdS, back contact barriers and processing effects. Transport parameters such as minority carrier diffusion length L, depletion width W, the effect of front and back junction on device performance and the origins of forward recombination current are not well correlated with the CdTe thickness t, carrier density, or back contact. A blocking back contact might be expected to decrease $V_{oc}$ yet seems to have little impact [1]. Part of the problem is that optoelectronic characterization is typically performed with light incident through the glass/$SnO_2$/CdS window. Due to the high absorption coefficient and low carrier density, the majority of light is absorbed in the high field CdS/CdTe junction depletion region. It is not possible to characterize the back junction, if one exists, or to probe transport in the neutral bulk.

We have developed semi-transparent electrodeposited Cu-doped ZnTe films for back contacts. The purpose of this type of a contact is to examine junction and transport properties by applying bifacial characterization techniques to CdS/CdTe solar cells [2]. For front illumination through CdS, the back junction is nominally in the dark. For back illumination through ZnTe:Cu, the front junction is in the dark so the results are not affected by photoconductive CdS. For t > W, most of the back illumination light is absorbed in the field free region (t-W) so that minority carriers (electrons) must diffuse to the depletion edge of the front junction. A bifacial device provides a tool to study photocurrent collection and back contact behavior previously unavailable with front illumination.

## EXPERIMENT

Semi-transparent polycrystalline ZnTe:Cu films were grown by galvanic deposition on glass/$SnO_2$:F/CdS/CdTe substrates. The CdTe was deposited by vapor transport was 3, 3.5, 5 and 8 µm thick. CdS thickness was 50nm, $SnO_2$:F was 350 nm, and ZnTe:Cu was ~50nm.

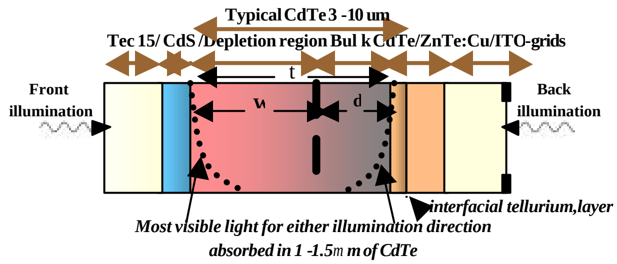


**Fig 1. A 5µm bifacial CdTe device, W=3µm, d=2µm**

**Table 1. Parameters for VT deposited CdTe devices**

| Device | Contact | Light | Voc mV | Jsc mA/cm$^2$ | FF (%) | Eff (%) |
|---|---|---|---|---|---|---|
| A1 7 um | ZnTe:Cu (BDH) | Front | 820 | 20.3 | 68.0 | 11.3 |
| | | Back | 660 | 0.60 | 66.3 | 0.20 |
| A2 7 um | Cu/Ni (BDH) | Front | 820 | 20.8 | 68.7 | 11.8 |
| B 8 um | ZnTe:Cu (Br-Me) | Front | 795 | 19.4 | 69.0 | 11.3 |
| | | Back | 625 | 1.4 | 67.0 | 0.20 |
| C1 5 um | ZnTe:Cu (Aniline) | Front | 812 | 22.2 | 68.1 | 12.3 |
| | | Back | 674 | 1.19 | 69.5 | 0.55 |
| C2 5 um | ZnTe:Cu (Br-Me) | Front | 804 | 22.4 | 67.0 | 12.0 |
| | | Back | 680 | 1.40 | 67.0 | 0.65 |
| D 3 um | ZnTe:Cu (Br-Me) | Front | 770 | 20.60 | 57.0 | 9.0 |
| | | Back | 632 | 3.10 | 61.0 | 1.1 |

The CdTe surface was first treated to remove any oxide present and create a $p^+$ interfacial Te rich surface necessary for a good ohmic contact. The three surface etchants used were either BDH(Bromine-methanol, then Dichromate, then Hydrazine); aniline; or Br-methanol. Sputtered ITO(200nm) and evaporated Ni/Al grids were contacts to the ZnTe:Cu. The bifacial device structure is shown in Fig 1. The JV parameters and CdTe thicknesses are shown in Table 1. ZnTe:Cu films on TEC 15 substrate had ~ 80% transparency in visible spectral region. Film deposition and characterization details are covered in [2]. Bifacial JV measurements were performed on these devices using filtered Xe lamp, simulating AM 1.5 spectrum at 25°C. Spectral response characterization was performed at different biases on devices with different CdTe absorber thicknesses with bifacial illumination. Numerical values of L and W were derived from SR analysis. The depletion width values obtained from SR analysis were independently confirmed by capacitance-voltage(C-V) measurements.

## RESULTS AND DISCUSSION

### Current Voltage (JV) Measurements

JV measurements were performed on these devices with the purpose of investigating the front heterojunction and the back contact separately. The device parameters with this contact are comparable to Cu/Ni metal contact and are shown in Table 1.

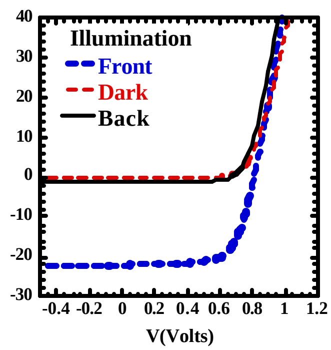


**Fig. 2A. Bifacial JV response of device C1 (No rollover)**

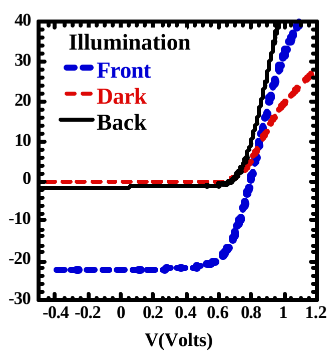


**Fig. 2B. Bifacial JV response of device C2 showing "Photoconductive back contact"**

Figs. 2A and 2B show the bifacial J(V) curves for two devices, C1 and C2 respectively, (t=5 µm)with ZnTe:Cu contacts but different CdTe surface treatments. For conventional optoelectronic characterization through the glass side, most of the light is absorbed with first micron of CdTe as shown in Fig. 1. Hence, the back contact is always in the dark. A transparent back contact allows transmission of light in the back contact region. Despite having similar performance, device C2 shows rollover in the forward bias region whereas device C1 does not. Usually, the roll-over(curvature) at forward bias in the J(V) curves for CdTe devices is attributed to blocking contacts. These results suggest that the blocking contact does not have a major impact on $V_{oc}$ and device efficiency. For device C2, the curvature in the forward bias response is seen only for the dark and front illumination. When illuminated through the contact side, the barrier is eliminated, suggesting that the blocking contact is "photo-sensitive". This effect was observed on devices irrespective of absorber thickness and surface treatments.

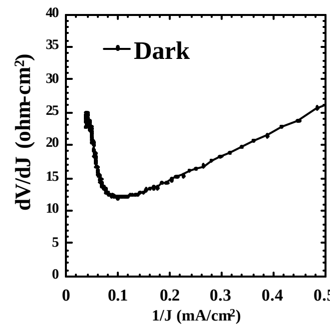


**Fig 3A. dV/dJ vs. 1/J dark for device C2**

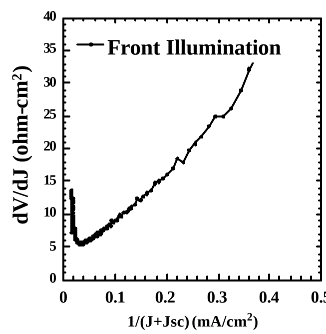


**Fig 3B. dV/dJ vs. 1/(J+Jsc), front illumination device C2**

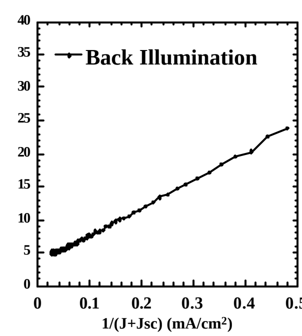


**Fig 3C. dV/dJ vs. 1/(J+Jsc), back illumination device C2**

A more definitive way to detect a blocking contact is from a plot of derivative dV/dJ response curve versus the inverse of the measured current density J [3]. A blocking barrier causes an inflection in the data as 1/J values decreases. Fig. 3A shows the plot for dV/dJ vs. (1/J) for dark and Figs. 3B and 3C show dV/dJ (r(J) vs. 1/(J+Jsc) for front and back illumination. Clearly the inflection at low values of 1/J is seen for the dark and front illumination but not for back illumination. This proves that the back barrier is photo-sensitive and can be removed by illumination.

It has been reported that the back contact creates a reverse [4] collecting junction(reverse field) and may result in negative SR at longer wavelengths. We have never seen evidence supporting this theory. SR data will be discussed in the next section.

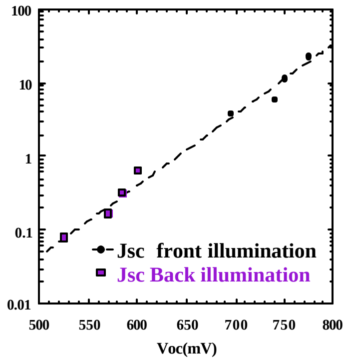


**Fig 4. $V_{oc}$ vs. $J_{sc}$ at different light intensities for either illumination direction for Device A1**

Fig. 4 shows $J_{sc}$ vs. $V_{oc}$ for back and front light at several intensities for device A1. Data for both illumination directions is fit with a single line $V_{oc}$= AkT/q log ($J_{sc}/J_o$) indicating that a single junction determines the recombination current regardless of illumination direction. This confirms the back junction does not influence the carrier collection or voltage for front light.

## Spectral Response (SR) Analysis

In this section we will use bifacial spectral response analysis on devices with ZnTe:Cu contact to derive L and W. A bifacial model developed for CIS devices [5] has been used to study CdTe solar cells. This model evaluates the internal front and back spectral response as a function of L, W and absorption co-efficient ($\alpha$). Model assumptions and description is covered in [5]. We fit the measured external $SR_F$ and $SR_B$ to this model using an error minimization routine after accounting for optical losses through the CdS and the back contact.

The width of the depletion region is a function of applied bias and has a high electric field that ensures effective carrier collection. In CdTe devices, W at 0V is a substantial portion of the bulk region. For conventional front illumination, most of the carriers are generated and collected in this high field region. The depletion width can be accurately determined by capacitance measurements but to date there is no acceptable technique to determine the diffusion length. The most common ones are reported in [6,7,8] and involve front spectral response measurements. The reported values of L in CdTe solar cells [8,9] range from 2µm-0.1µm. There is negligible effect of L on $SR_F$ as, ($1/\alpha$) >> W >> L and for front illumination, most of the carriers are effectively collected. Here we show a technique to accurately determine the values of both W and L using back spectral response that was measured by illumination through the back contact. Fig. 5 shows the measured and fitted SR at 0V for a 5 um thick device. There is good agreement between the fitted and the measured data. This validates the model used for bifacial spectral analysis. $SR_B$ which is used to obtain the transport parameters L and W is unaffected by optical CdS loss in range 400-700nm.

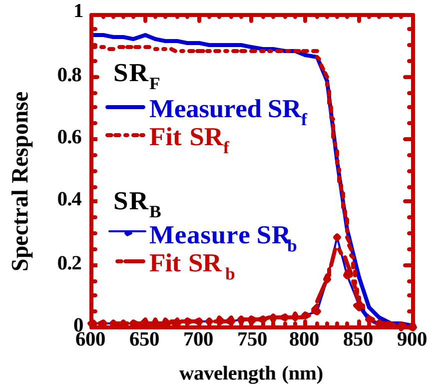


**Fig 5. Measured and fitted $SR_F$ and $SR_B$ at 0V for t=5µm, W=2.2µm, L=0.71µm**

The region from 600-800 nm is referred to as the tail of the response that is very sensitive to the diffusion length. $SR_b$ value at 830 nm is called the peak of the response and is affected by the depletion width W. Fig. 3 shows $SR_B$ measured at –1V, 0V and +0.5V for device from the same batch as devices C1 and C2. The fitted values were obtained with t=5 µm, L=0.7 µm and W decreasing with increasing bias: 3.2, 2.8 and 2.0 µm.

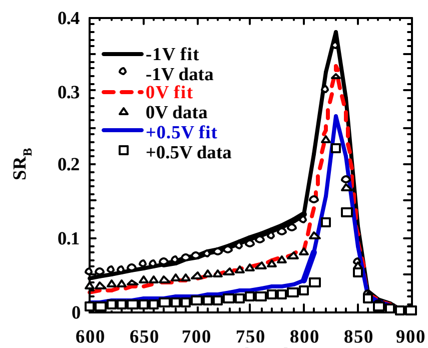


**Fig 6. $SR_B$ for (t=5 µm) at 3 voltage biases**

The fit is quite good. For back illumination, electron diffusion across the neutral CdTe bulk (t-W) to the junction depletion region is represented by the tail from 600 to 800 nm for comparison. The depletion width W was also evaluated by capacitance voltage (C-V) measurements. The values for W and L deduced from $SR_B$ analysis and W values measured by C-V are shown in Table 2. There is excellent agreement for W for devices with different absorber thicknesses. Carriers generated in the depletion region by weakly absorbed near-bandgap light (800-860 nm) are collected with high probability, represented by the spike from 800-860 nm in Fig 6. The depletion width of ~2 μm at even at +0.5V also verifies the assumption that most AM1.5 light is absorbed in the high field region for front illumination. Future work will involve investigation of possible reasons for increase in W with CdTe thickness.

**Table 2. W(V) obtained from $SR_B$ analysis and C-V**

| Sample | Thickness (μm) | L(μm) | W(μm) | | | |
|---|---|---|---|---|---|---|
| | | | @ (-1.0V) | | @ (0V) | |
| | | | SR | CV | SR | CV |
| B | 8 | 0.76 | 5.5 | 5.4 | 4.8 | 4.8 |
| C1 | 5 | 0.72 | 2.6 | 2.4 | 2.4 | 2.0 |
| D | 3 | 0.6 | 1.8 | 1.7 | 1.3 | 1.4 |

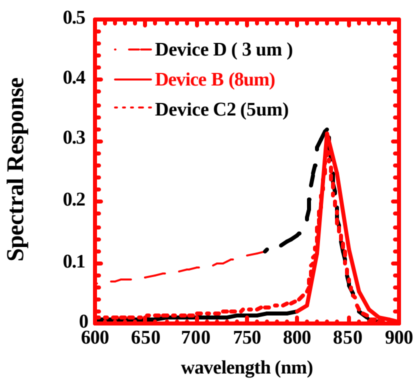


**Fig 7. $SR_B$ for devices with different CdTe thickness**

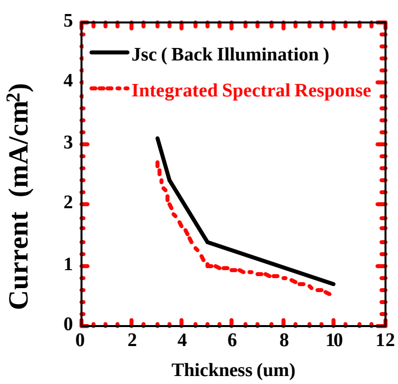


**Fig 8. Measured $J_{sc}$ and integrated SR for back illumination**

Fig. 7 shows $SR_B$ for cells with different CdTe thickness. As t increases, the distance carriers must diffuse (t-W) increases, hence the diffusion tail (<800 nm) decreases. This correlates to the fact that the measured $J_{sc}$ for back light was higher for the thinner cells. There is a good agreement between the integrated spectral response and measured $J_{sc}$ as shown in Fig 8. Decreasing bias V reduces W and is qualitatively the same as increasing t.

Both increase the distance t-W which carriers generated by back illumination must diffuse. We have not observed negative SR on any of the devices even though roll-over was observed (device C2) in the JV response. Hence, we can say that the back contact barrier does not have opposite polarity from the CdS/CdTe heterojunction.

## CONCLUSION

The results presented in this paper provide a quantitative understanding of minority carrier transport parameters in CdTe based photovoltaic devices. We have demonstrated that bifacial device characterization is a valuable and efficient tool for analysis of the primary transport parameters and allows separation of the primary CdS/CdTe junction from the back contact. We conclude that for standard front illumination, the fill factor (FF) and $SR_F$ are limited by voltage dependent collection and L is nearly irrelevant. However, $SR_B$ is limited by diffusion through the bulk to the depletion edge. W and L were derived by extensive numerical analysis of $SR_B$ data. The values of W obtained were independently confirmed by C-V measurements, thus validating the numerical model and the analysis procedure. The blocking contact usually observed in CdTe devices is photoconductive and can be effectively eliminated by illumination. This blocking contact barrier has no effect on $V_{oc}$. Hence, it can be concluded that there is no secondary junction present.

## ACKNOWLEDGEMENTS


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